Multi-TSO system reliability: cross-border balancing

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***Abstract*—This paper develops a stylized analytical model that analyses reliability management of multiple TSOs. First we analyse the possibilities for TSO cooperation on reserves dispatch and procurement, with a focus on European network codes. Then we propose a model that theoretically analyses cross-border reserve cooperation. We distinguish two degrees of cooperation: reserves exchange and reserves sharing. Our model first determines the non-cooperative TSO equilibrium i.e. the autarkic provision of reserves. Next we compare this with the socially optimal (cooperative) policy of generation reserves procurement. The paper shows why reserves sharing is economically superior to reserves exchange. Sharing allows cost arbitrage and pooling of reserve needs while reserves exchange only takes care of cost arbitrage. The benefits of reserves exchange and reserves sharing depends on cost asymmetry and correlation of reserve needs between the TSO zones.**

***Index Terms*—Cross-border balancing, generation reserves, multi-TSO interactions, power system reliability**

I. Introduction

The main short-term responsibility of the Transmission System Operator (TSO) in a deregulated electricity market is to manage the security of the transmission system. Since demand has to equal supply at all times but a perfect forecast of demand and supply is not possible, in order to maintain the reliability of the grid, the TSO has to deal with imbalances in real time using upward and downward reserves. The imbalances can be exacerbated due to increased penetration of intermittent solar and wind generation [1]. In addition, the available reserves should also be able to deal with large and sudden imbalances caused by failures of transmission or generation components. As today transmission networks are interconnected between different countries, and the imbalances due to intermittent power increase, the number of unscheduled flows rises [2]. This trend increases both the need for reserves and the costs for procurement and dispatch of these reserves. This paper shows that cooperation between adjacent TSOs on reserves dispatch and procurement reduces this cost.

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The benefits of TSO cooperation in reserves and balancing have already been studied in the literature. A case-study example describing the balancing done between Belgium and Netherlands is presented in [3], who conclude that introduction of a balancing market between those two countries is a ”lucrative and achievable goal”. A more general conclusion - that coordination of European balancing markets done by TSOs should be one of the next steps towards the harmonisation of electricity markets into the EU Internal Electricity Market (IEM), is reached by [4]. Also [5] discuss similar issues and quantify the benefits of inter-market benefits using a stylised 4-node network. Likewise, [6] quantify the benefits of cooperation and study the effects of transmission constraints.

Our paper employs a probabilistic approach and explicitly incorporates costs and benefits of cross-border reserve procurement. Such an approach is increasingly used to assess the gains and the complexities of probabilistic criteria for transmission reliability management [7] - [11].

Although the topic of integrated balancing markets is present in the literature, to the best of our knowledge, there is still a lack of understanding, whether and to what extent TSO reliability management actions and interactions of generation reserves scheduling, as imposed by reliability criteria in network codes, are economically efficient for the region as a whole. Furthermore, these reliability criteria impose the levels of required reserves and thus determine a certain reliability level, without any reference to balancing the costs of reserves and interruptions.

The contribution of this paper is a general model that analyses three degrees of TSO cooperation in reserves provision. First, we examine autarkic TSO reserve provision - a non-cooperative TSO equilibrium. Then we study reserves exchange when a TSO can acquire reserve capacity in the adjacent TSO area. The last case investigates reserves sharing. Reserves sharing amounts to maximising the surplus of the two nodes jointly and it allows both a cost arbitrage and pooling of reserve needs. We show why reserves sharing is economically superior to reserves exchange. We also present a numerical example in order to provide an illustration of the three scenarios.

This paper consists of seven sections. In Sections II and III we review some of the ideas relevant to this paper, based on the European network codes, and we explain the characteristics of the different reserve categories. Section IV explains how different TSOs can cooperate in reserve provision. Section V introduces the main model that analyzes three degrees of TSO cooperation. In order to illustrate the ideas of this paper, we set up a numerical illustration in Section VI. The last section concludes.

II. Network codes

Efficient power system reserves management consists of three tasks:

1) Procure the correct level of reserves: dimensioning.
2) Efficient procurement of reserve: procure the cheapest reserve capacity first.
3) Efficient dispatch of reserves: dispatch the cheapest reserve capacity first.

In this paper we only consider the first two tasks.

Most transmission systems consist of different interconnected networks, which are each governed by one TSO. Since system frequency is shared on all voltage levels of a synchronous area, due to the technical characteristics of electricity, power system reliability is considered to be a common good. That is, a non-excludable but rival good. This means that a MW of power can only be used once and that it is technologically difficult to prevent interconnected TSOs from using more than they provide. Underprovision of reserves in one TSO zone could thus lead to a widespread blackout throughout the synchronous area. Therefore, to prevent this ‘Tragedy of the Commons’, all TSOs in a synchronous area are obliged to provide sufficient reserves.

Within the European transmission system, rules on reserve procurement and dispatch are formulated in two network codes:[1] the network code on Load-Frequency Control and Reserves (NC LFCR) [12] and the network code on Electricity Balancing (NC EB) [13]. These network codes also deal with TSO cooperation in balancing and reserves. TSOs can cooperate in three ways: (1) exchange of reserves, (2) reserves sharing, and (3) imbalance netting. Section IV-B will explain this in more detail. Currently, cooperation between TSOs is widespread in forward markets, the day-ahead market (e.g. flow-based market coupling) and the intraday market (e.g. Elbas in Nord Pool). However, cooperation in balancing and reserves is still limited [14]. Section IV-C lists some examples of current reserve cooperation between Central European TSOs.

III. Reserve categories

A myriad of different reserve product specifications and balancing processes exists, differing in the response time, ramp rate, availability, procurement procedure, bid selection, bid activation, minimum bid size, bid resolution, settlement procedure, nomination time, etc. However, European TSOs are required by ENTSO-E’s network code on Electricity Balancing (NC EB) to harmonize these products and procedures to a certain extent in coming years. The network code on Load-Frequency Control and Reserves (NC LFCR) divides reserve products into three main categories: (1) Frequency Containment Reserves (FCR), which stabilizes the frequency after a disturbance, (2) Automatic and Manual Frequency Restoration Reserves (aFRR and mFRR), which brings the frequency back to its setpoint value, and (3) Reserve Replacement (RR), which replaces the active reserves such that they are available to react to new disturbances. FCR are dimensioned and distributed within a synchronous area, i.e. over multiple TSOs, while activation of FRR and RR is the responsibility of the TSO whose area is disturbed. Fig. 1 summarizes the role and sequence of activation of the different reserve products.

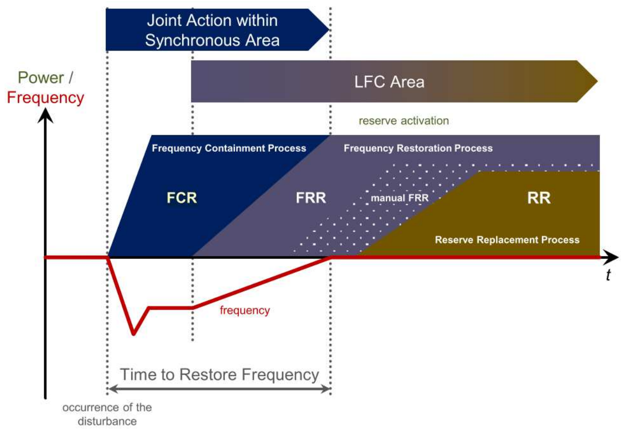

Fig. 1. Role and sequence of activation of the different reserve products: FCR, aFRR, mFRR and RR [15]

IV. TSO cooperation

A. Reserve dimensioning

A first step in reliability management is determining the correct level of each of the different kind of reserves. In Europe, the dimensioning of FRR and RR is done at the level of the Load Frequency Control (LFC) block. Most LFC blocks consist of one TSO[2] who is responsible for managing the area. The dimensioning rule requires procured reserves to be sufficient to deal with the largest imbalance, the so-called dimensioning incident (DI), from tripping of one demand facility, one HVDC interconnector, one power generating module or one AC line within the LFC block.

Dimensioning of FCR capacity is done at the level of the synchronous area. That is, total procured FCR capacity in the synchronous area should be able to deal with the largest imbalance from tripping of two connection points, two power generation modules or two HVDC interconnectors. The FCR capacity that is determined from this rule is evenly distributed within the synchronous area. When a component

[1] Soon to be adopted as European Regulation

[2] Examples of exceptions: LFC block Germany exists of four LFC areas, each governed by one TSO; Spain and Portugal constitute an LFC block.

of the synchronous area fails, FCR capacity will react in all TSO zones of the synchronous area, as shown in Fig. 1.

B. Exchanging and sharing reserves

TSO cooperation can increase efficiency in reserves management in at least two ways:

(A) **Cost arbitrage**: if the reserve market is enlarged, expensive reserves can be substituted for cheaper procurement and dispatch of reserves.

(B) **Pooling of reserve needs**: less reserve capacity is needed if idle reserve capacity can be used in neighboring TSO zones in need of capacity.

According to the network codes, TSOs can cooperate in three ways:

- **Exchange of reserves** makes it possible to procure part of the required level of reserves in adjacent LFC blocks. These reserves are exclusively for one TSO, meaning that they cannot contribute to meeting another TSO's required level of reserves. This is an exchange of contractual obligations between TSOs. That is, the reserve capacity remains in the reserve-providing TSO zone, however, if needs arise the exchange results in physical delivery of power to the reserves-receiving TSO.
- **Reserves sharing** allows multiple TSOs to take into account the same reserves to meet their reserve requirements resulting from reserve dimensioning.
- **Imbalance netting** avoids counteracting activation of balancing energy in adjacent TSO zones.

Exchange of reserves only allows cost arbitrage (A), while reserves sharing allows both cost arbitrage and variance-reducing pooling of reserve needs (A)+(B). However, in practice reserves exchange and sharing is not limitless. Table I summarizes the limits of the NC LFC&R on the quantity of reserves sharing and exchange between LFC blocks within a synchronous area.

TABLE I
LIMITS ON EXCHANGE AND SHARING OF RESERVES BETWEEN LFC BLOCKS AS FORMULATED IN THE NETWORK CODE ON LOAD-FREQUENCY CONTROL AND RESERVES [12]

	Exchange	Sharing
FCR	30% min in own LFC block 30% max per adjacent LFC block & <100MW per adj. LFC block	Not allowed
FRR	50 % min in own LFC block	Decrease of FRR $<$ 50% & $< \lvert DI - FRR(99\%)\rvert$
RR	50 % min in own LFC block	Decrease of RR $<$ 50%

That is, minimally 30% of dimensioned FCR capacity, and 50% of FRR and RR capacity, needs to remain physically in the own LFC area. The term $|DI - FRR(99\%)|$ means that the decrease of FRR capacity cannot be larger than the difference between the initial dimensioning incident and the reserves needed to meet the reserve need in 99% of the time.

The FCR volume is determined for the whole synchronous area and each TSO must ensure its initial FCR obligation. Sharing of FCR is not allowed as this would reduce the overall available FCR for the synchronous area. Thus the only option for cross-zonal cooperation in FCR is exchanging FCR balancing capacity. Doing so, TSOs do not physically exchange FCR between countries but take over initial obligations from other TSOs.

C. Examples

Balancing and reserve cooperation between European TSOs is still in its infancy. However, a few examples of successful cooperation exist:

- aFRR is jointly procured by all German TSOs.
- Elia procures part of its FCR obligations in France.
- Tennet (NL+GE) and Elia share part of their mFRR (300MW).
- Common procurement of FCR in Germany, Switzerland, Austria and the Netherlands.
- Belgium, the Netherlands, Germany, Denmark, Czech Republic, Switzerland and Austria have implemented a system of imbalance netting.

V. MODEL

Our model studies reserves sharing and exchange between two TSO zones $i = 1, 2$. The need for reserves in TSO zone i at a certain instant is r_i [MW]. This is the imbalance in real time due to a combination of forecast errors of demand and intermittent supply, and failures of generation capacity or transmission components. We denote the joint probability density function of the reserve needs r_i by $f(r_1, r_2)$; r_1 and r_2 are assumed to be non-negatively correlated and jointly normal with known parameters. The TSO's variable of choice is R_i [MW], the quantity of reserves procured.[3]

In this paper we are interested in efficiency gains from exchange or sharing of reserve procurement, not efficient dispatch as such. Hence, the model does not take generation dispatch into consideration and we therefore take marginal generation costs to be equal to zero. Costs of procuring R_i MW of reserve capacity in TSO zone i, however, are not zero and are given by $\gamma_i(R_i)$, with γ_i increasing, smooth and convex.

We only model reserve needs in the first quadrant of the two-dimensional space of reserve needs (r_1, r_2). Reserve needs in the second and fourth quadrant, i.e. when the reserve needs have a different sign (imbalance netting), are irrelevant when generation costs are zero. The analysis for reserve needs in the third quadrant, i.e. for negative reserve procurement, is similar to the analysis of positive reserve procurement.

A. Order of Events

The order of events is as follows:

Ex-ante (before uncertainty is realised):

1. The TSO at node i chooses how much reserve capacity R_i to procure.

Ex-post (after uncertainty is realised):

[3]Even though section III explained the different reserve categories in some detail, for simplification we neglect in this model differentiation between different kinds of reserves (FCR, aFRR, mFRR and RR).

2. In real time the actual need for reserves r_i is observed in each node i.
3. The procured reserves will be used to accommodate the reserve needs. In case local reserves are insufficient, TSOs will use exchanged or shared reserves, or carry out load shedding.
4. Settlement payments are paid.

Note that the choice of reserve capacity could be for different time horizons, e.g. for an hour, a week, a month, or a year. The probability density function $f(r_1, r_2)$ will in general depend on the procurement interval and the time to real time operation. In case of exchange or sharing of reserves, the procurement entails payments between TSOs.

B. Autarkic TSO reserve provision

We first consider the case where there is no trade or exchange of reserves between zones. Thus, each TSO zone operates as an isolated "island". The dimensioning rules, as explained in section IV-A, define how much reserves each LFC area is required to procure. The dimensioning incident was one component failure for FRR and RR, and a joint failure of two components for FCR. Here we pursue an alternative approach by assuming that TSO i procures a quantity of reserves R_i such that expected social surplus in zone i is maximized. That is, he selects R_i to maximize $E[S_i]$ with respect to R_i, where

$$E[S_i] = v(D_i - \int_{R_i}^{\infty} (r_i - R_i) f(r_i)\,\mathrm{d}r_i) - \gamma_i(R_i), \quad (1)$$

and v is the value of lost load (VOLL) [€/MWh]. Gross surplus from electricity consumption is the product of VOLL and electricity demand D_i. Interruption cost is the product of VOLL and the quantity of unserved expected demand (given by the integral in (1)). Net consumer surplus is the difference of these two terms. Social surplus in zone i, S_i, is given by consumer surplus less the cost of procuring reserves.

The optimal reserve capacity in autarky, $R^*_{i,a}$, is determined from the following first-order condition:

$$v\mathrm{Pr}\{r_i > R_i\} = \gamma_i'(R_i), \quad (2)$$

which is obtained by differentiating (1). The intuition of this condition is that reserves are procured up to the point where the marginal cost of interruptions - given by VOLL times the loss of load probability - equals the marginal cost of providing that level of reserves.

It is easily seen that the second-order condition for maximum of $E[S_i]$ is satisfied.

C. Reserves Exchange

As explained earlier, reserves exchange makes it possible to procure part of the required level of reserves in adjacent TSO zones. We assume that sufficient transmission capacity is available to always accommodate the flows arising from use of reserve capacity in adjacent TSO zones. That is, there is only load-shedding if $r_i > R_i$, irrespective of where the reserve capacity is procured. Exchange of reserves only allows cost arbitrage, not pooling of reserve needs. Here we assume, compliant with the network codes, that the required level of reserves in each TSO zone is the same as in autarky, i.e. $R^*_{i,a}$. We also assume that the two TSOs jointly minimise total costs of procurement, subject to the constraint on reserves. That is, cheapest reserve capacity in the two TSO zones is procured first. This amounts to the following constrained cost minimization:[4]

$$\min_{R_1,R_2} \gamma_1(R_1) + \gamma_2(R_2) \text{ s.t. } R_1 + R_2 = R^*_{1,a} + R^*_{2,a}. \quad (3)$$

This leads to the following set of equations:

$$\begin{cases} \gamma_1'(R_1) = \gamma_2'(R_2) \\ R_1 + R_2 = R^*_{1,a} + R^*_{2,a}. \end{cases} \quad (4)$$

That is, costs are lowest when the marginal cost of reserve procurement is equal in all TSO zones. Fig. 2 shows this cost minimization graphically. The axis runs from left to right for TSO zone 1 and from right to left for TSO zone 2. Clearly, if costs are symmetrical in the two zones, then there is no reason to exchange reserves and the optimal solution is for each TSO to procure reserves within his own zone. If costs are asymmetrical, then there is a rationale for exchange. The grey area in the figure is this reduction of procurement costs under a pay-as-bid system. The costs of the reserves-providing TSO (Zone 1 in the figure) will clearly rise so, to make this arrangement incentive compatible, the reserves-receiving TSO needs to pay the reserves-providing TSO an amount that at least covers the latter TSO's costs.[5]

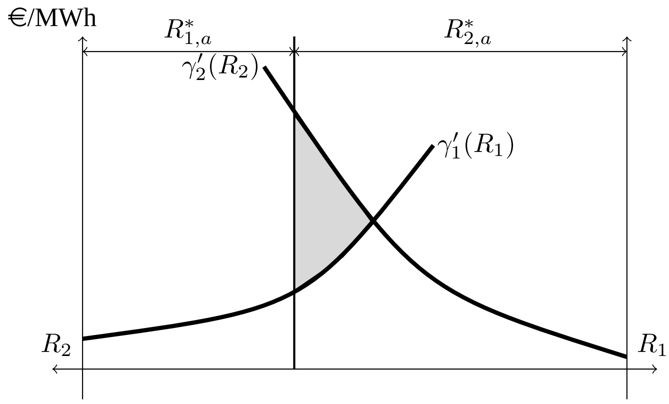

Fig. 2. Cost minimization under reserves exchange between two TSO zones

Reserves exchange allows the reserves-receiving TSO to procure reserves more cheaply than under autarky. However, the cost-minimization does not incorporate the VOLL and does not allow to change the quantity of reserves, i.e. it does not maximize expected surplus. Likewise, reserves exchange

[4] As a simplification, we neglect any limits on reserves exchange, as explained earlier in table I.

[5] The behaviour of the two TSOs and the contract needed for cooperation is not studied in detail in this paper. TSOs could have an incentive to act strategically while cooperating with adjacent TSOs. For example by distorting the congestion signal in cross-border congestion management [16] or by spending too little on network maintenance [17].

does not exploit the possibility of pooling reserve needs with adjacent TSOs.

D. Reserves Sharing

Reserves sharing allows multiple TSOs to draw on the same reserves resources to meet their required level of reserves when it comes to operation. It allows both cost arbitrage and pooling of reserve needs, including sharing of interruptions if necessary. As before, we assume that transmission capacity is sufficient to always accommodate the flows arising from use of reserve capacity in adjacent TSO zones. That is, there is only load-shedding if $r_1 + r_2 > R_1 + R_2$. In our model, reserves sharing amounts to maximizing the surplus of the two nodes jointly, i.e. maximizing $E[S_1 + S_2]$.[6] Expected social surplus in the two zones together may be written as

$$E[S_1 + S_2] = v(D_1 + D_2 - \int_0^\infty \int_{R_1+R_2}^\infty (r_1 + r_2 - (R_1 + R_2)) f(r_1, r_2)\, \mathrm{d}r_1\, \mathrm{d}r_2) - \gamma_1(R_1) - \gamma_2(R_2). \quad (5)$$

The optimal reserve capacities when reserves sharing is allowed, $R^*_{1,S}$ and $R^*_{2,S}$, are determined from the following first-order conditions:

$$\begin{cases} v\mathrm{Pr}\{r_1 + r_2 > R_1 + R_2\} = \gamma_1'(R_1) \\ v\mathrm{Pr}\{r_1 + r_2 > R_1 + R_2\} = \gamma_2'(R_2), \end{cases} \quad (6)$$

which are derived by differentiation of (5) with respect to R_1 and R_2, respectively. The intuition for this set of first order conditions is to procure reserves in each TSO zone up to the point where the total marginal cost of interruptions, i.e. the product of VOLL and the loss of load probability (LOLP) in the two zones jointly, equals the marginal cost of providing that level of reserves.

The first-order equations imply that marginal costs of reserves procurement are equal to VOLL times the loss of load probability in the two zones together. Clearly, this implies that marginal costs of procurement are equal at the optimal levels of procurement. Hence, the costs of reserves procurement are minimized as in reserves exchange, but for different levels of reserves and, hence, also reliability.

E. Comparing the three cases

The comparison of the three scenarios yields that the overall expected social surplus with reserves sharing is higher than with reserves exchange. This follows from noting that reserves exchange is a constrained version of reserves sharing. Moreover, the overall expected social surplus with reserves exchange is higher than that in autarky, which is the case unless the zones are fully symmetric, since costs of reserves procurement are lower and interruption costs are the same.

Another important thing to note is that when the zones are asymmetric, there will be distributional consequences of reserves exchange. Reserves costs will fall in one zone and rise in the other. There is a minimal payment that will suffice to make exchange incentive compatible. There will still be a surplus that may be split in some way between the two zones, e.g. by Nash bargaining. However, we do not consider this issue here.

With reserves sharing, there may also be distributional consequences that make one zone better off and the other worse off, both as regards reserves costs and expected interruptions. Similarly to reserves exchange, for incentive compatibility of sharing there will be a minimal side payment from the better off zone to the one that is worse off.

[6] As a simplification, we neglect any limits on reserves sharing, as explained earlier in table I.

VI. Illustration

In this section we present a numerical example to illustrate the comparison of the three regimes (autarky, reserves exchange and reserves sharing). The base case for the illustration is that the probability density functions of reserve needs are jointly normal with correlation ρ, each with a mean of 10 MW and a variance of 5 MW: N(10,5). The cost of reserve procurement is $\gamma_i(R_i) = c_i R_i^2$. Table II shows the results of this numerical illustration.

The first three columns show procured reserves in each of the TSO zones and the sum of all procured reserves, for each degree of cooperation. The fourth column expresses total procured reserves relative to the procured reserves in autarky. The fifth column shows the total cost, which is the sum of expected interruption costs and procurement costs in both TSO zones. The last column expresses the total cost relative to the autarky cost.

The first part of the table shows the results of a symmetric case, i.e. marginal procurement costs are equal in the two TSO zones. The correlation coefficient is zero. In the second part of the table, procurement cost is twice as high in TSO zone 1, while the correlation coefficient increases from zero to one.

TABLE II
RESERVES AND COSTS IN TSO ZONE 1 AND 2: RR = RELATIVE RESERVES; TC = TOTAL COST; RC = RELATIVE COST.

$c_1 = c_2 = 2$	R_1	R_2	R_1+R_2	RR	TC	RC
Autarky	15.05	15.05	30.10	100%	998.4	100%
Exchange	15.05	15.05	30.10	100%	998.4	100%
Sharing $\rho = 0$	13.63	13.63	27.26	90.5%	801.7	80.3%
$c_1 = 4, c_2 = 2$						
Autarky	14.46	15.05	29.50	100%	1431.9	100%
Exchange	9.83	19.67	29.50	100%	1303.7	91%
Sharing, $\rho = 0$	8.97	17.95	26.92	91.3%	1046.1	73.1%
Sharing $\rho = 0.5$	9.46	18.93	28.39	96.2%	1178.8	82.3%
Sharing $\rho = 1$	9.87	19.74	29.61	100.4%	1295.3	90.5%

This illustration shows several important issues. In the first case, when the two TSO zones are identical, no cost arbitrage is possible and exchange of reserve does not yield any cost reduction. However, reserves sharing leads to a lower reserve need and thus a lower cost. In the second case, when the cost of reserve procurement is higher in TSO zone 1, reserves exchange does yield a cost reduction. TSO 1 procures part of its reserve obligation with reserve capacity providers in

TSO zone 2. The resulting cost reduction, between autarky and exchange, of 128.2 €/h can be a gain for TSO 1, TSO 2 or distributed between both (e.g. through Nash bargaining). In reserves sharing, costs are evidently even lower. Again, how this cost reduction is distributed over the two TSOs depends on the details of the inter-TSO contract. The table shows that the cost reduction decreases when the reserve needs in the two TSO zones are more correlated. When the reserve needs are fully correlated, reserves sharing yields almost no additional cost reduction compared to reserves exchange.

Lastly, the total procured reserves do not always decrease with reserves sharing. When costs are asymmetric but reserve needs are highly correlated, the decreased procurement cost due to cooperation could entail more reserves to be procured optimally, i.e. a higher reliability level. Fig. 3 summarizes the cost reductions of this illustration.

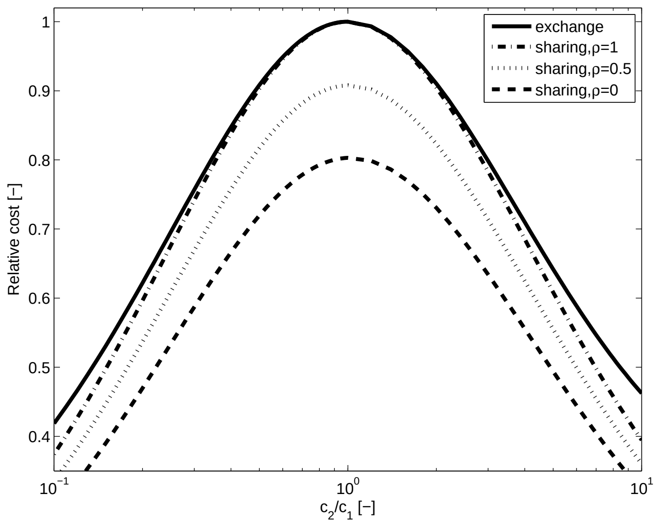

Fig. 3. Relative cost (compared to autarky) with reserves exchange and reserves sharing, as a function of the cost asymmetry and the correlation ρ between the reserve needs.

This figure shows that the cost reduction increases when reserve procurement costs become more asymmetric and reserve needs are less correlated. With low cost asymmetry and low correlation, reserves sharing yields the major part of the cost reduction, while with high cost asymmetry and a high correlation, reserves exchange yields the major part of the cost reduction. With symmetric costs and high correlation, cross-border cooperation in reserves yields very little cost reduction.

VII. Conclusions

This paper compares three degrees of TSO cooperation in generation reserves provision: autarky, reserves exchange and reserves sharing. We derive analytically, in a relatively stylized model, the optimal procurement of reserves in each of the three cases and show that costs, which are expected to rise with increasing penetration of renewable generation, decrease with cooperation. The benefits of reserves exchange and reserves sharing depends on cost asymmetry and correlation of reserve needs between the TSO zones. That is, when TSO zones have highly asymmetric reserve procurement costs but highly correlated reserve needs, reserves exchange already yields a high cost reduction. When TSO zones have fairly equal reserve procurement costs but a low degree of reserve needs correlation, reserves sharing is needed to reap the full benefits of TSO reserves cooperation.

National electricity markets are increasingly interconnected in Europe, spurred by European Regulations, Directives and network codes. In the day-ahead market there has been considerable progress in coupling national markets at the regional level, however, cooperation in balancing and reserves has been minimal and limited to a few voluntary agreements. The Network Code on Electricity Balancing discusses how TSOs ought to cooperate. This paper shows analytically the cost reduction for different degrees of cooperation. A next step is to include transmission constraints and analyse the effect on the benefits of multi-TSO cooperation.

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